Vertical Structure of the Convective Surface Layer

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(Manuscript received September 21, 1981)

Abstract

The vertical structure of the atmospheric surface layer under very unstable conditions is investigated based on a field experiment. Relations between the fluxes and the vertical correlations or coherences of the turbulent fluctuations at various heights indicate that the organization of the convective system plays important roles in the transport of both heat and momentum.

1. Introduction

The buoyant convection in the atmospheric boundary layer when the surface heating is strong occurs in the form of organized plumes. In the middle and upper part of the atmospheric boundary layer, airplane or captive balloon measurements (Warner & Telford[1], and Kaimal et al.[2]) indicate that plumes are well organized and clearly distinguished from the quiescent region surrounding the convective elements. In the lowest part of the boundary layer (the surface layer), because of the predominant mechanical turbulence, the convective elements seem to be more random and less organized. However, when the wind speed is low, the level of the plume organization reaches as low as a few meters above the ground. Various sizes of convective plumes are observed in the surface layer. These convective plumes are observed to be tilted toward the downwind direction and to be translated at the speed of wind of some height. This was found a few tens of years ago (e.g. Priestley[3]), and several investigators followed to clarify the structure and the translation of the convective plumes (Kaimal & Businger[4], Davison[5], Kaimal[6]), but there are still a number of uncertainties left unsolved.

A plume is believed to be a form of convection which has an effiecient mechanism to transport energy from the surface to the upper part of the boundary layer. There are a number of theories to determine the structure of the buoyant plumes and the vertcal heat fluxes in the plumes (e.g. Morton et al.[7] and Telford[8]). However, these theories are only valied for the upright plumes in the wind field without vertical shear. No theories have been developed which can be applied to the surface layer convection.

Experimentally, also, the understandings concerning the transport mechanisms of the heat and the momentum through the plumes are unsatisfactory. The bulk transfer mechanisms, in which the fluxes are assumed to be proportional to the product of the air-surface difference of the quantities and the mean wind speed, break down under the free convective conditions. The objective of this research is to clarify if the organization of the convective activity promotes the vertical transport of heat and momentum by examining the relation between the transport and vertical correlation of turbulent fluctuations at various heights in the surface layer.

2. Experimental procedure

The experiment was carried out over grass land (grass height about 20 cm) in the field of the Wind Effect Laboratory at Shionomisaki. The experimental field was located on a flat plateau which has a slope at its southern end. There were a few small buildings scattered near the site. The largest laboratory building was located to the south of the field. Therefore, the southern wind may be distorted and those data were omitted from the analysis. The examination of the homogeneity based on the results will be discussed in the following section.

Sonic anemometers and resistance thermometers were installed at 4 heights (15.1, 6.7, 2.6 and 1.3 m) on the 15 m tower erected in the center of the experimental field. The sonic anemometer at 15.1 m height is 3-dimensional (Kaijo-Denki SAT-311) and others are 1-dimensional (Kaijo-Denki DAT-300) installed to measure the vertical component. The resistance thermometer consists of a tungsten wire of 10 μm in diameter. The response of these sensors are better than 70% up to 10 Hz in normal meteorological conditions and fast enough to measure the detailed structure of the thermal convection in the surface layer. Aspirated diode thermometers were installed to measure the mean temperature at 14.8 and 1.0 m height on the same tower. The surface temperature was measured by an infrared radiation thermometer (Barnes PRT-5). A typical grass surface was selected near the tower, and the radiation thermometer was installed at 1.2 m height with the angle of 66 degrees from the vertical. This means that the area of the measured surface had a diameter of about 15 cm since the view angle is 2 degrees.

Observation was carried out during the period when a travelling high covered the area in late November, 1979. During the period of about 3 hours in November 20, which we analyzed here, there were no visible cloud in the sky, the average wind speed was 1.5 m/s, and the wind direction was variable from NW to NE, which are relatively good directions for the site.

The signals from the fast response instruments (the sonic anemometers and the tungsten wire thermometers) were recorded by an analog tape recorder in FM form. The recorded signals were digitized at 20 Hz with the 10 Hz low pass filter before the analysis. The 8 runs (each contains 10 minutes) are chosen from the period between 10 to 13 hours JST.

3. Temperature and velocity field of the convection

Time variations of the mean and the statistical quantities of the whole analyzed period are indicated in **Fig. 1**. The temperature at 15 m height increases gradually at the rate of about 0.13°C/10 min but the state may be assumed as steady considering the large temperature fluctuations ($\sigma_\theta \sim 0.7$°C typically). The surface temperature seems to reach its maximum earlier than that of air, and the air-surface temperature difference decreases gradually. The wind is variable between 0.67 and 2.36 m/s. Variations of the variances and turbulent fluxes are larger in the upper layers. The vertical variations of the standard deviation of the vertical wind fluctuations and the temperature fluctuations obey approximately the $z^{1/3}$ and $z^{-1/3}$ law respectively as derived from the free convection hypothesis (**Fig. 2**). The height variations of

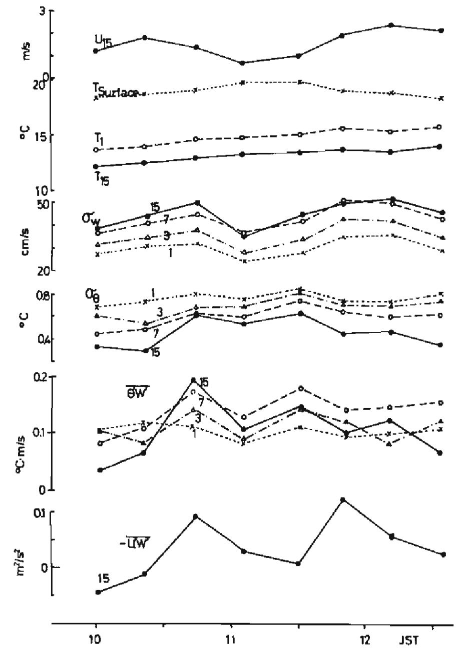

Fig. 1. Time variations of the mean and the statistical quantities for the analyzed period. The numbers in the graph represent the height in meters.

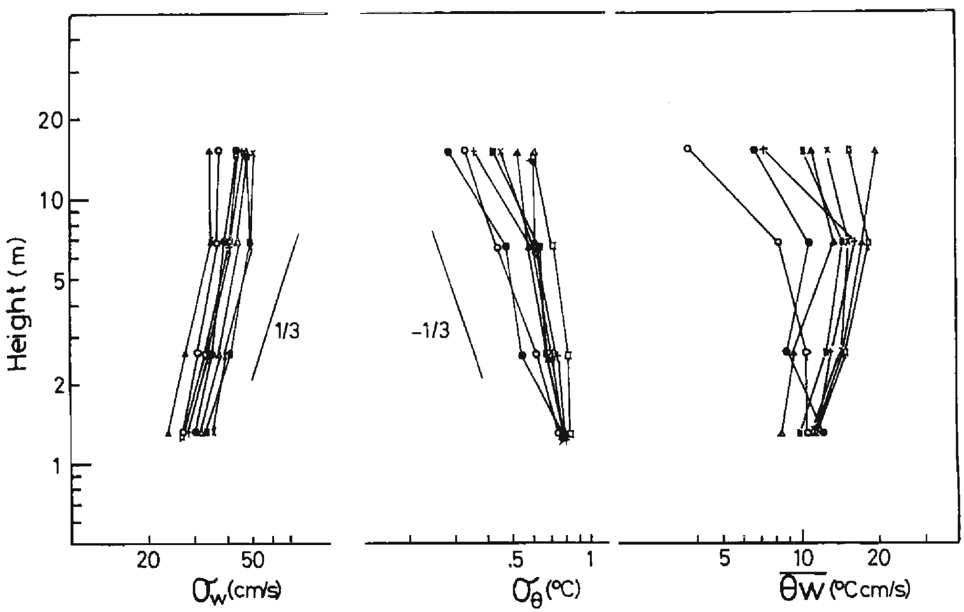

Fig. 2. Vertical distributions of the rms of the vertical velocity and temperature fluctuations, and the covariance between these fluctuations.

the sensible heat flux for each run seems to exist, but there is no strong tendency to decrease or increase with height if averaged. Considering these height variations, we may regard this experiment as having been carried out over a reasonably homogeneous field at least for the analyzed period.

The momentum or the sensible heat flux does not seem to vary similarly with wind speed as seen in **Fig. 1**. It may also be reasonable to suppose that the bulk transfer method does not apply to the free convective conditions, since heat flux may be expected even when there is no mean wind, if the radiation heating is strong. It is also known that the bulk transfer coefficient for momentum (or the drag coefficient C_D) and the heat (C_H) are difficult to determine when wind speed is low. For example, increase of C_D with decreasing mean wind speed is observed (Mitsuta & Tsukamoto[9)]). **Fig. 3** shows no dependence of $\overline{u'w'}$ on U^2, or $\overline{\theta'w'}$ on $U\cdot(T_s-T_{15})$. The mechanism of the transport should be searched for in the systematic behavior of the organized convection. Even upward momentum fluxes are sometimes observed under free convective conditions (Kaimal & Businger[4)]). The positive $\overline{u'w'}$ is also observed in a few runs in this experiment. This upward momentum transport seems to occur when the convective activities are suppressed vertically. We recognize that the structure of the air flow in the convective plumes should be responsible for this negative viscosity.

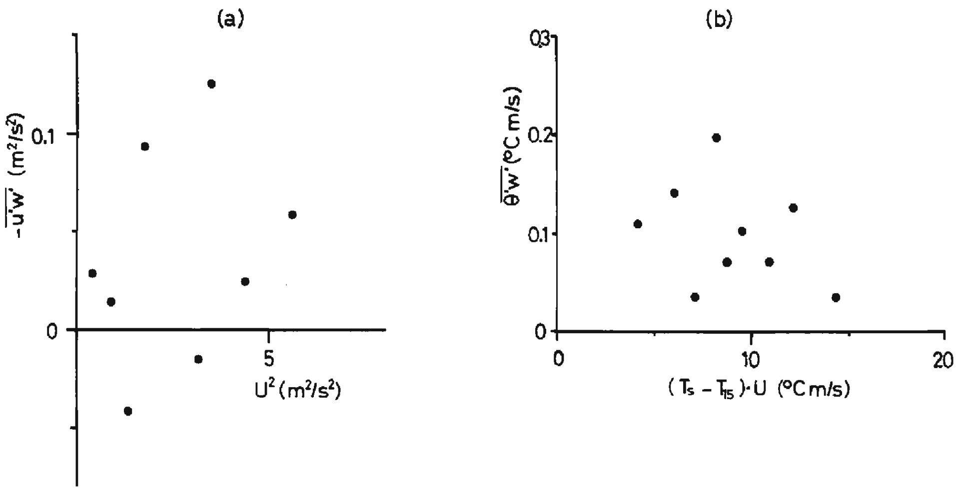

Fig. 3. The relation between the momentum flux (covariance $\overline{u'w'}$) and the wind speed squared (a), and between the heat flux (covariance $\overline{\theta'w'}$) and the air-surface temperature difference multiplied by the wind speed (b).

One example of the time-height cross-sections of the temperature excess, vertical velocity and the product of these quantities is illustrated in **Fig. 4**. The temperature excess is defined as the deviation from the temperature of the quiescent region. Two distinct convective elements are recognized in this period. From the vertical continuity of the phenomena, we may assume these convective elements are plumes. The average wind speed at 15 m height for this period is 1.6 m/s. Therefore the apparent diameter of the plumes is about 20～30 m if plumes are assumed to travel with this speed. The plume on the right suggests that the plume defined by the

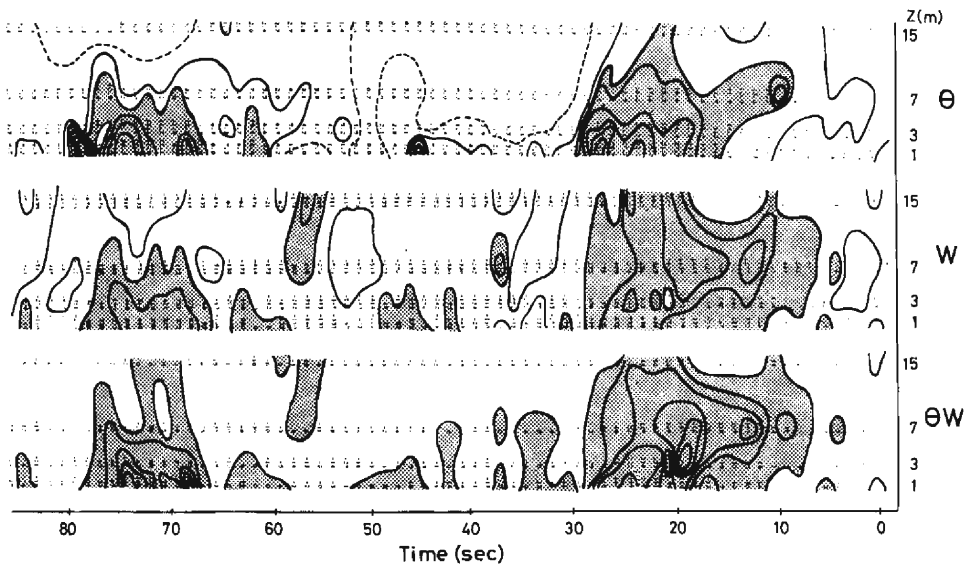

Fig. 4. An example of the time-height cross-section. The solid contours of θ, w and θw are drawn every 0.5°C and 0.5 m/s and 0.5°C m/s respectively, and the shaded region corresponds to the area of θ larger than the quiescent region more than 1°C, $w>0$ and $\theta w>0$ respectively.

temperature excess is tilted downwind, and the upwind edge of the plumes has a sharp temperature gradient. On the other hand, the vertical wind distribution is more upright and does not seem to have the sharp upwind front. This difference is also identified in the vertical correlation as will be seen in the following section.

4. Vertical correlations

As seen in **Fig. 4**, the most outstanding feature of the convection in the surface layer may be the vertical continuity of the phenomena. One of the methods to measure the vertical continuity may be to compute the correlation function among the various levels. For the temperature fluctuations, it is defined as

$$R_{\theta_i\theta_j}(\tau)=\frac{1}{S}\int_0^S \theta_i(t+\tau)\theta_i(t)dt/(\sigma_{\theta_i}\cdot\sigma_{\theta_j})$$

where τ is the time lag, S the sampling duration and the suffices i and j represent two heights. The average correlation functions in the τ-z plane over 8 analyzed runs are indicated in **Fig. 5** and **Fig. 6**. In these figures the correlation coefficients between the lowest (1.3 m) and other levels (2.6, 6.7 and 15.1 m) are indicated. Differences between the vertical wind correlation (**Fig. 5**) and temperature correlations (**Fig. 6**) reflect the characteristics which appeared in **Fig. 4**. The correlation of the vertical velocity components does not indicate clear delays or advances of the phenomena at higher levels, which suggests that the phenomena is almost upright. On the other hand the temperature fluctuations advance at higher levels

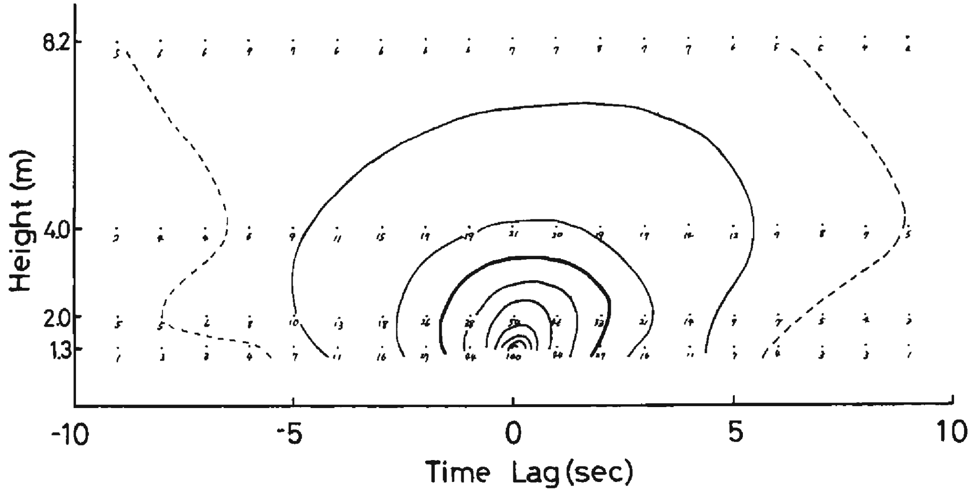

Fig. 5. The average correlation coefficient of the vertical velocity between 1.3 m and other heights. The solid contour is drawn every 0.1. The thick line is the contour of 0.3.

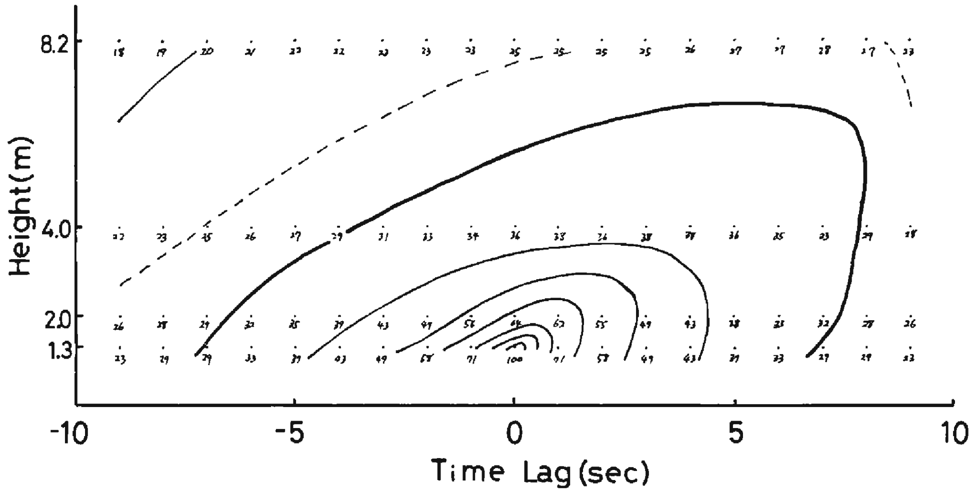

Fig. 6. Same as Fig. 5 except for the temperature.

in about 5 seconds on the average. The value of the coefficients for the temperature fluctuations are almost twice as large as those for the vertical velocity.

The correlation functions among the individual runs vary considerably. The time lag for the temperature between 1.3 and 15.1 m varies from zero to 1 sec/m. The convection is sometimes suppressed and therefore the correlation is small but in some cases extended upward. The correlation coefficient for temperature has always positive values, but in the vertical velocity correlations, negative values are often observed.

The time lag in the temperature correlations are supposed to be caused by the tilt of the plumes in the downwind direction. According to Kaimal & Businger[4], the tilt angle (elevation angle β is used here) is determined by the ratio of the stretching and the vertical wind shear in the surface layer. The stretching is the rate of the increase of the vertical velocity component and supposed to act as the force to erect the plumes. On the other hand the shear may force the plumes to tilt toward the downwind direction. Thus the convective plumes are supposed to have an angle determined by stretching and shear. It may be resonable to assume the ratio of the free convection velocity w_* and the friction velocity u_* defined respectively as

$$w_* = \left(\frac{g}{T} \cdot \overline{w'\theta'} \cdot z\right)^{\frac{1}{3}}$$

and

$$u_* = \sqrt{-\overline{u'w'}}$$

is proportional to tangent of the elevation angle of the plume from the horizontal surface as

$$\tan \beta \propto \frac{w_*}{u_*}$$

However, as seen in the present set of data, u_* is difficult to determine under convective conditions since positive $\overline{u'w'}$ occurs frequently. Mean velocity U is applied here instead. **Fig. 7** indicates that β increases with w_*/U. In this figure β is determined assuming that the convective element travels with wind as the entity, i.e., $\tan \beta = \Delta z/(\bar{\tau} \cdot U)$, where $\bar{\tau}$ is the mean time lag for the height difference Δz. **Fig. 7** shows that the plumes may become upright when w_* reaches about one half of the wind speed. Further detailed analysis indicates that $\bar{\tau}$ is more sensitive to U than w_*.

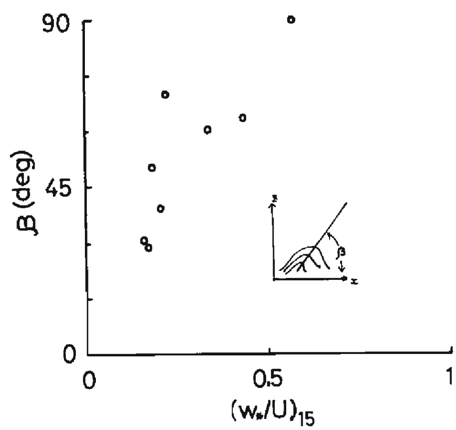

Fig. 7. The relation between the plume tilt and the ratio $w_*/\bar{U}$ at 15 m.

As mentioned previously the value of the correlation coefficient for the temperature fluctuations at different levels is expected to be closely related to the vertical transport of the heat and momentum. In order to express the vertical extension of the phenomena, we may define a scale as

$$z_\theta = \int_0^h R_{\theta_i\theta_j}(0)\,dz$$

Although, since the integration is only possible up to 8.2 m, and $R_{\theta_i\theta_j} \neq 0$ at this level ($z=h$), this scale z_θ is smaller than the true integral scale, z_θ may be a good

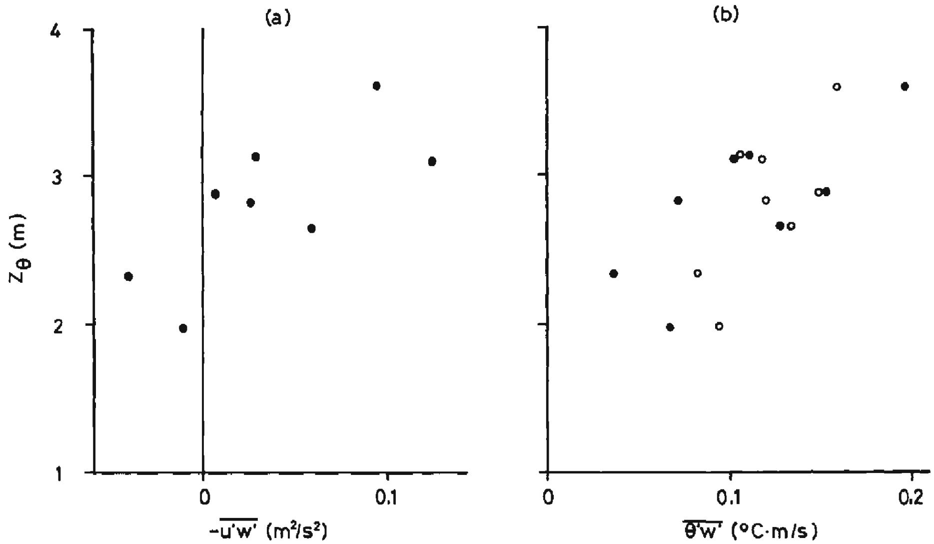

Fig. 8. The relation between the vertical integral scale z_θ for the temperature fluctuations and the momentum flux (a), and the heat flux (b). The dots denote the flux measurement at 15.1 m, and the circle the average value of 4 levels.

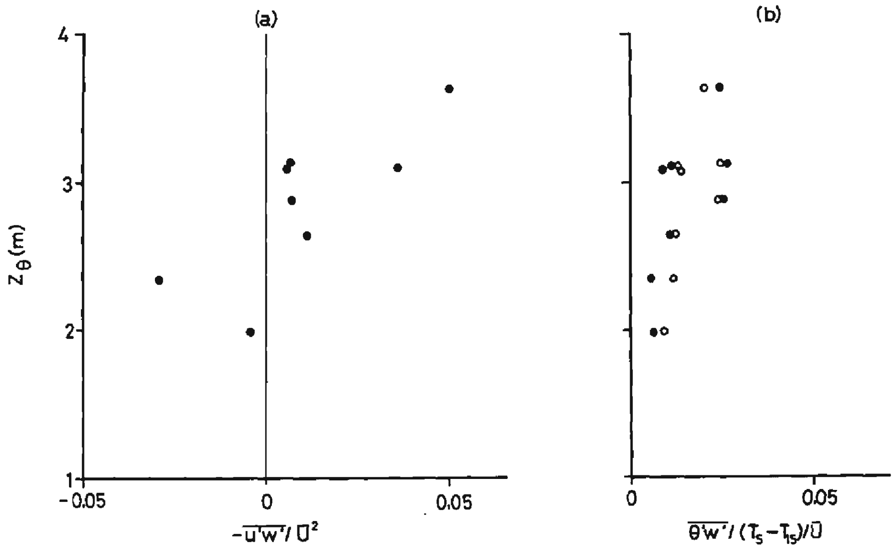

Fig. 9. Same as Fig. 8, except normalized by U^2 and $(T_s - T_{15})\cdot U$, respectively.

measure to indicate how deep the phenomena are related vertically, or how the convection is active. As seen in **Fig. 8**, a large z_θ corresponds to a large vertical transport. The momentum and the heat fluxes normalized by U^2 and $U\cdot(T_s-T_{15})$ respectively are called the drag coefficient (C_D) and the bulk heat transfer coefficient (C_H). Although it is not certain at present whether these bulk transfer coefficients are appropriate parameters to be considered in the free convective conditions, they seem to behave as well as the flux itself (**Fig. 9**). The vertical scale for the vertical velocity correlation z_w is smaller compared to z_θ about 60% and does not seem to vary systematically with the fluxes. The reason for this has not been understood.

5. Vertical coherence

The correlation coefficient described in the previous section may include all the scales analyzed in the sampling period. Since the plume scale is important here, it may be more desirable to limit the analysis in the specific scale range. The scale of the convective activity may be defined as the scale of maximum heat flux, which is the peak frequency of the $\overline{\theta' w'}$ cospectrum. The peak of the cospectrum falls in the frequency range between 0.01 and 0.1 Hz or the wave length range between 200 and 20 m. An example of the heat flux cospetra for one run is shown in **Fig. 10.** The heat flux cospectrum measured at various heights often has the peak in the same frequency range in free convective conditions and this scale range may be defined as the free convection scales as pointed out by Monji[10]. The vertical coherence at these frequency ranges of the convective scales is estimated below.

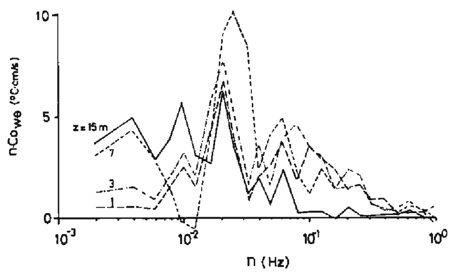

Fig. 10. An example of the cospectra between the temperature and vertical velocity.

Influences of the buoyant plumes seem to appear in the coherence function. Both the vertical coherences of the vertical velocity and those of the temperature indicate a definite peak in the convective scale range defined by the heat flux cospectra (**Fig. 11**), and may not be represented by the exponential shape as often assumed in the horizontal coherences of the horizontal velocity component (see e.g. Iwatani[11]), although the averaged coherences may be closer to the exponential function as shown in **Fig. 12.**

The value of the temperature coherence at the plume scale defined from the $\overline{\theta' w'}$ cospectral peak may be the measure of the vertical connection by the buoyant plumes. The momentum and heat fluxes should be well correlated with the value of the coherence of this scale range as shown in **Fig. 13**. The fluxes are larger

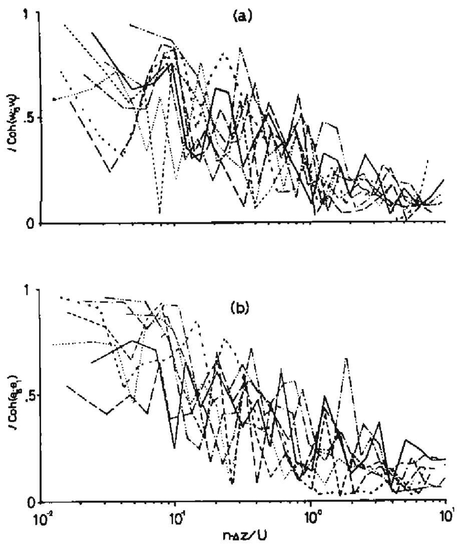

Fig. 11. Coherence between two levels (15.1 and 1.3 m) of the vertical velocity (a), and the temperature (b).

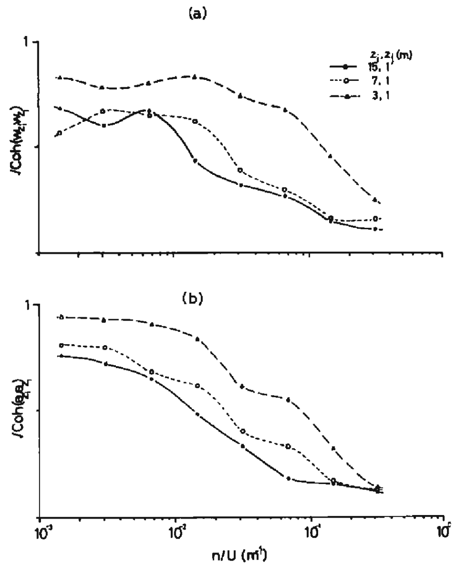

Fig. 12. Averaged coherence function for the observation period of the vertical velocity (a) and the temperature (b) fluctuations.

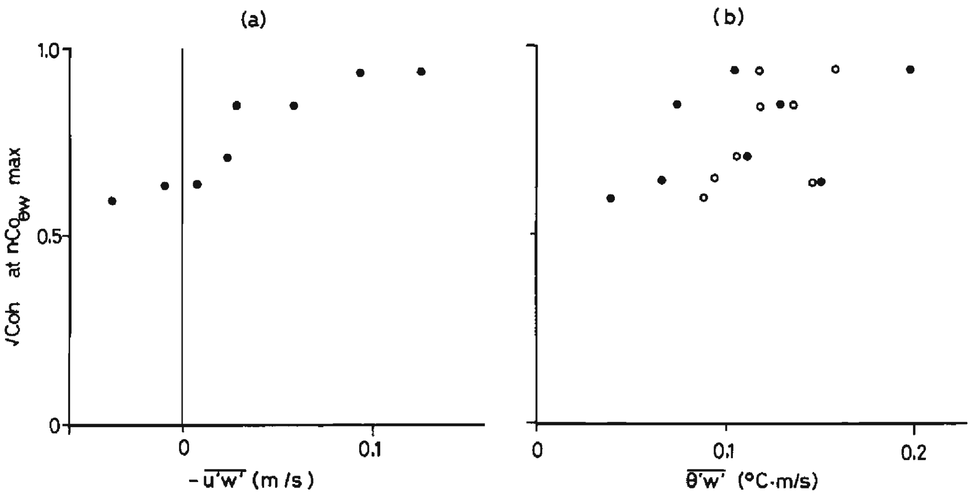

Fig. 13. Relation between the temperature coherence and the momentum flux (a), and heat flux (b). The value of the coherence between 15.1 and 1.3 m height is obtained from the scale of the maximum heat flux.

when the coherence is closer to unity. Again the drag coefficient is found to be closely related to the coherence (**Fig. 14**) suggesting that the vertical connection of the phenomena makes the vertical momentum transport easier. Or, in other words, the plumes act as the path of the vertical transport. On the other hand, the bulk heat transfer coefficient does not behave so well. This might suggest

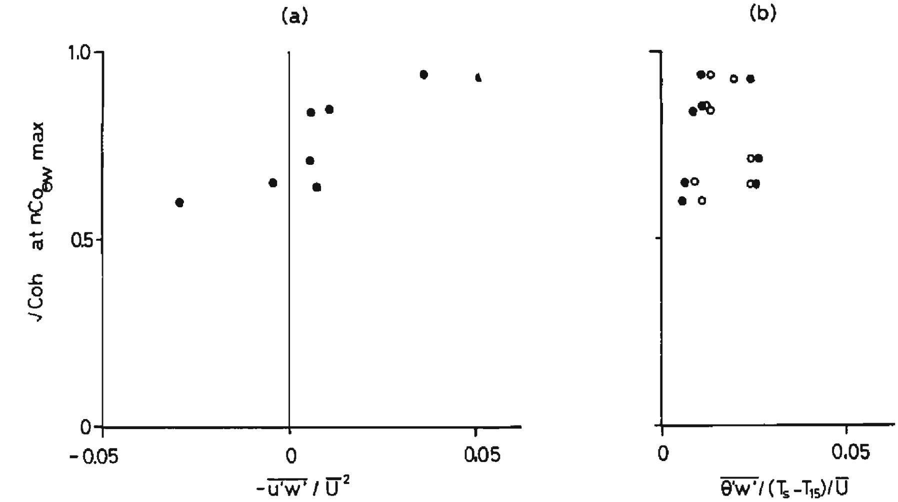

Fig. 14. Same as Fig. 13 except normalized by U^2 and $(T_S-T_{15})\cdot U$ respectively.

the inadequacy of the bulk heat transfer concept under free convective conditions.

6. Conclusion

The vertical structure of the surface layer up to a height of 15 m under free convective conditions is investigated based on the vertical velocity and temperature fluctuations at four heights, and the following results are obtained:

1) Temperature field is well correlated vertically. The average vertical integral scale is 2.9 m. The larger the vertical integral scale, the larger are the momentum and the heat fluxes. The time lag of the correlation is usually larger at higher levels, which is probably influenced by the tilt of the buoyant plumes.

2) Vertical velocity field, on the other hand, is less correlated vertically. The average vertical integral scale is 1.8 m. The vertical integral scale for w is not related to the turbulent fluxes.

3) The vertical coherence both vertical velocity and temperature at the convective scale defined by the scale of the maximum heat flux is well related to the turbulent momentum and sensible heat fluxes.

To summarize the conclusion, the convective system acts to transport momentum and heat efficiently. In other words, the plumes may act as the path of the vertical transport.

Several problems are left unsolved. The differences between the correlation function of the temperature $R_{\theta_i\theta_j}$ and the vertical velocity $R_{w_iw_j}$ and the negative viscosity phenomena could be explained if the flow structure inside and outside of the convective plumes were clarified. Three dimensional observation would be necessary to establish the entire flow model of the convective plumes .

Acknowledgement

The author wishes to acknowledge the staff at Shionomisaki Wind Effect Laboratory for their technical assistance during the experiment. This research was supported by The Ministry of Education, Science and Culture under the Grant-in-Aid for Scientific Research No. 454109.

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